RIVER FLOW

P. Carling
Department of Geography, Highfield, Southampton University, UK

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Contents

Summary

This chapter presents a range of key concepts that enable natural rivers to be understood as complex flows of water and sediment that interact and often result in changes to the channel shape. The implications for salmon fisheries and invertebrates are also considered. Rivers are linear features and so it might be supposed that the flow hydraulics would be unidirectional and relatively simple to describe. To some extent this is true. Except for the largest of the world rivers, the effects of wind-waves and geostrophic circulation can be ignored, as can periodically reversing flow which dominates tidal reaches. However, to complicate matters, rivers are characterized by relatively rapid changes in flow rate and consequently can be regarded as stationary in behavior only over short time spans. The relative shape and roughness of the channel may change as water levels fluctuate, and the twisting and turning of meandering channels means that often water is spiraling and only short reaches can be considered as linear conduits.

Despite complexities, the relatively two-dimensional nature of many rivers has meant that engineers have been able to describe the flow structure present by two-dimensional or even one-dimensional flow models with sufficient accuracy for most practical applications. However, all rivers are characterized by turbulent flow, and large rivers in particular have a complex three-dimensional structure that can be well described only by sophisticated mathematical modeling, scaled by laboratory data.

It is clear that there are a number of levels of increasing complexity at which the natural river system can be described. It is important to decide at which level of complexity observations should be made to obtain answers to problems and to consider whether

genuine understanding can be obtained at any one level. For example, at the most basic level a good correlation may be obtained between the behavior of an organism and mean current speed when in fact it is the level of turbulence intensity that is really controlling behavior. However, moving to a higher level of explanation may not be productive if too many assumptions are required to produce a 'working' model of hydraulic structure.

1. Introduction

Rivers are linear features and so it might be supposed that the flow hydraulics would be unidirectional and relatively simple to describe. To some extent this is true. Except for the largest of the world rivers, the effects of wind-waves and geostrophic circulation can be ignored, as can periodically reversing flow which dominates tidal reaches. However, to complicate matters, rivers are characterized by relatively rapid changes in flow rate and consequently can be regarded as stationary in behavior only over short time spans. The relative shape and roughness of the channel may change as water levels fluctuate, and the twisting and turning of meandering channels means only short reaches can be considered as linear conduits.

Despite complexities, the relatively two-dimensional nature of many rivers has meant that engineers have been able to describe the flow structure present at any one moment by two-dimensional or even one-dimensional flow models with sufficient accuracy for most practical applications. However, all rivers are characterized by turbulent flow, and large rivers in particular have a complex three-dimensional structure that can be well described only by sophisticated mathematical modeling, scaled by laboratory data obtained using delicate apparatus. The latter are usually not suitable or are difficult and expensive to use in real rivers.

It is clear, then, that there are a number of levels of increasing complexity at which the natural river system can be described. It is very important to decide at which level of complexity observations should be made to obtain answers to problems and to consider whether genuine understanding can be obtained at any one level. For example, at the most basic level a good correlation may be obtained between the behavior of an organism and mean current speed when in fact it is the level of turbulence intensity that is really controlling behavior. However, moving to a higher level of explanation may not be productive if too many assumptions are required to produce a 'working' model of hydraulic structure. For many applications, sophisticated explanation is neither necessary nor cost effective. As Peters and Goldberg (1989) observed, average data may well describe the environment, and standards exist that assume temporal stability of simple phenomena (Gore 1978, Newbury 1984). Peters and Goldberg (1989) further noted that the field scientist frequently 'has to rely on rough, robust apparatus, often lacking sensitivity' and consequently it is important to consider what can realistically be achieved when designing any field monitoring or experimental program. The tools available must be capable of providing at least a degree of insight into the problem of interest.

With these limitations in mind, a considerable degree of understanding can be obtained by those who appreciate the complexities of natural flow structure even if they are unable to describe fully many phenomena mathematically. To this end, this article aims to provide a practical approach to dealing with the intricacy of hydraulics and sediment transport within the context of recent research related to real rivers, and to emphasize those methods that are likely to be fruitful in practical applications. It is not possible within the space available to describe all procedures fully but details can be found in the references cited.

2. The Near-Bed Boundary Layer

Fluvial currents are driven by gravitational gradients, either imposed by the nature of the terrain or as modified by fluvial erosion and deposition and the quantity of water delivered to the channel. In turn, the structure of the flow is mediated by the friction induced by the channel boundary. In deep rivers the region where the frictional effects are felt, the *boundary layer*, may occupy only a small proportion of the total depth whilst in shallow rivers it may extend to the water surface. Laminar (non-turbulent) flow never occurs throughout the full depth in natural rivers, so that it is turbulence which transfers frictional forces throughout the fluid and redistributes suspended particles. Further, turbulence intensity mediates the momentary level of shear stress exerted on the boundary which may result in the movement of bed and bank sediments so modifying the shape and capacity of the river channel. A consideration of the velocity structure is therefore of prime importance.

Turbulent flow may be divided into smooth, transitional and rough hydrodynamic regimes. Such a consideration is required to select appropriate equations to describe the velocity structure. For flat sand-beds the division may be given by considering the roughness Reynolds number, a non-dimensional ratio defined by the shear velocity (u_*, defined below), the grain size (D) and the kinematic viscosity (v):

Smooth turbulent: $u_* D / v < 3.5$ (1a)

Transitional: $3.5 < u_* D / v < 68$ (1b)

Rough turbulent: $u_* D / v > 68$ (1c)

The ratio expresses the balance of inertial and viscous forces. Where bed roughness is due to gravel or ripples, for example, then D (the grain size) needs replacing by some other characteristic roughness length (k_{si} Table 1). The Reynolds number, with the length defined by flow depth, will be referred to again in Section 5.3

k_s is the equivalent roughness, u_* is the shear velocity, and v is the kinematic velocity (0.013 cm^2s^{-1}, 10°C, freshwater).

The time-averaged velocity (denoted as U, ignoring the usual over-bar) usually increases from zero at the bed to the free-stream velocity (U_x) at the edge of the boundary layer where the water is sufficiently deep to exceed the boundary layer thickness (Fig. 1(a)). However, in shallow flow the boundary layer may extend close to the surface (Fig. 1(b)).

Bed type	k_s (cm)	$u.$(cm s^{-1})	$u.k_s/v$	Regime
Smooth mud	0.006	1.2	0.5	Smooth
Smooth sand	0.03	2.2	5	Transitional
Dunes	15	2.8	3000	Rough
Flat gravel bed	1.5	3.6	400	Rough
Rocks	>30	4.6	$>10^4$	Rough

Table 1: Assessment of probable hydrodynamic regime
(*Reproduced with modification from Soulsby* (*1983*))

The theoretical structure of the flow can be divided into sublayers. The layer closest to the bed, the *bed layer*, is usually thin, often only a few millimeters thick. In slow flow over smooth beds (such as clay) it may be termed the *laminar sublayer*. In natural flows, however, the laminar nature may be disrupted. Local distortions in the velocity profile and turbulence levels then exist within the bed layer. The theoretical thickness of the laminar layer (δ) in *ideal* flow can be estimated using the relationship:

$$\delta = 11.5v/u \qquad (2)$$

The value of the constant can vary between 8 and 20 (Chriss & Caldwell 1983) but in rough turbulent flow over a gravel bed, where the calculated thickness is only millimeters, the layer is disrupted and often absent. In general, if the bed roughness value is greater than the calculated thickness of δ, then the latter is absent.

Many ecological texts argue that invertebrates are adapted morphologically to live within a laminar layer (see references in Statzner & Holm 1982), but Carling (1991) has argued that in many streams invertebrates that venture out of the interstitial environment are subject to low current speed but *high shear stress and turbulence levels,* a point made by Décamps and co-workers (1972, 1975) but largely ignored in contemporary literature.

Above the bed layer is the *logarithmic layer* (Figs. 1(a) & 1(b)), the basic form of which is neither affected by the local roughness of the bed nor by the free-stream flow structure. As its name implies, the structure can be described by logarithmic functions. This latter is very important, as measurements taken within it allow estimation of the shear stress acting on the bed. Usually it extends over 10-15% of the depth and may extend to the surface.

To estimate the boundary shear stress, it is important not to include current readings in the outer layer (Figs.1(a) & 1(b)), where the flow may be non-logarithmic. The usual relationship for the log-layer in the rough turbulent regime is:

$$U_z = (u./k)\ln(z/z_0) \qquad (3)$$

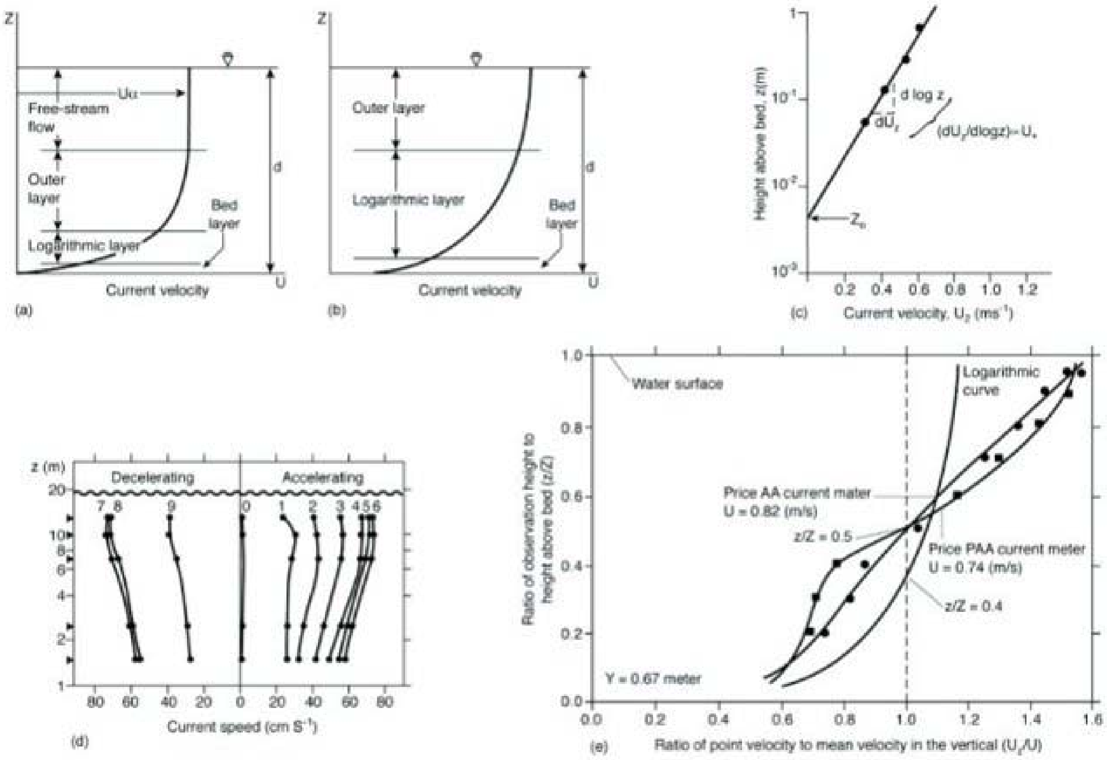

Figure 1: (a) Structure of the boundary layer in deep flow.(b) Structure of the boundary layer in shallow water. (c)Velocity profile data used to estimate *u*, (the shear velocity) and z_0 (the roughness length). (d) Effect of unsteady flow on profile shape (after Soulsby 1983). (e) Development of S-shaped profiles over very rough bed (after Jarrett 1990)

where von Kármán's constant (k) equals 0.40, and the roughness length (z_0) scales with the roughness of the river bed (Table 1). An estimate of z_0 can be obtained assuming $z_0 = D/30$ for sand or $D/15$ for well-sorted gravel, whilst the roughness of periodic bed-forms depends on height and spacing (e.g. Wooding *et al* 1973). Estimates of u_* and z_0 can be obtained from a regression analysis of current speed (U_z) against the height (z) above the bed (Fig. 1(c)). The shear stress (τ_0) is related to u as $\tau_0 = \rho u^2$. However, profiles should be plotted to ensure that the data conform to the logarithmic model, otherwise incorrect values of u_* and z_0 may be obtained.

The structure of the outer layer may be influenced by the free-stream velocity and consequently may not be described by any universal relationship. It is worth noting that the common practice of assuming that the depth-averaged velocity in the profile exists at 0.6 of the depth assumes that the logarithmic profile extends to the surface (Walker 1988).

Although Fig.1(c) is a true representation of an idealized velocity profile, the logarithmic profile may be distorted by such effects as acceleration or deceleration (Fig.1(d)), extreme bed roughness (dunes or large rocks, Jarrett 1990), or bank drag which may suppress the filament of maximum velocity to below the water surface

(Fig.2). In the case of large-scale roughness an S-shaped profile may be present with a logarithmic section close to the bed and a further log-profile at some distance from the bed (Fig.1(e)). If this reflects the influence of two scales of roughness (Dyer 1971), respectively that induced by the size of the bed material and that owing to the size of larger projections such as dunes, then each section of the log-profile may be treated separately to estimate the frictional effect of both roughness scales (Paris 1989). However, such an approach is open to criticism and where the height of the bed roughness is of the same order as the water depth no accepted theory exists to describe the vertical current structure.

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Biographical Sketch

Paul A. Carling worked at the NERC Institute of Freshwater Ecology at Windermere in England from 1977 until 1994 as a sedimentologist and hydrologist. From 1994 until 1999 he was Professor of Physical Geography and Director of the "Hydrodynamics and Sedimentology Research Laboratory" within the Institute of Environmental and Natural Sciences at Lancaster University. In March 2000 he took up the post of Professor of Physical Geography and Director of the Centre for Environmental Sciences at the University of Southampton.

His research interests span fluvial geomorphology and sedimentology including the interface with geological, engineering and biological sciences. Current themes include palaeofloods, bedform dynamics, turbulent-mixing processes in gravel and bedrock channels and overbank flood processes in UK rivers. Additional interests include; partitioning the control of climate versus landuse on the rainfall-runoff relationship in upland catchments; and the sustainable management of UK soils under forestry operations and the physical spawning habitat of salmon and trout. The majority of research involves international collaboration most recently with scientists in the UK, Canada, Germany, Thailand, Japan and Siberia. In 2003, with his co-author Dr. Z. Cao, he won the Institute of Civil Engineers' Telford prize for a paper entitled "Mathematical Modelling of Alluvial Rivers: Reality and Myth. Part 1: General Review".

Recent fluvial research is sponsored by the NERC, EPSRC and by DEFRA and is concerned with mixing processes in rivers, floodplain flow, the development of innovative tracers for gravel bedload and the development of software for managing salmonid spawing gravels adversely effected by siltation. British Council and Royal Society funded projects are investigating changes in rainfall-runoff in Thailand and gravel and sand dune development in UK and Polish rivers. Paul has a long-term commitment with Russian colleagues to decipher the Pleistocene history of large-scale catastrophic flooding in southern Siberia.